All-optical diode in a periodically poled lithium niobate waveguide

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We have demonstrated a guided-wave all-optical diode based on engineered quasiphase Matching in a $LiNbO_3$ channel waveguide. For input peak powers beyond 1.5 W at 1.55 μm, the device exhibited a spatially nonreciprocal response, leading to optical isolation with contrasts as high as 90% at 3.1 W, in agreement with theoretical predictions.
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Recent years have witnessed a renewed interest in integrated-optics alternatives to standard bulk Faraday rotators in optical isolators for fiber telecommunication systems. However, most thin film devices proposed or demonstrated to date rely on the magneto-optic effect.[1]

Since a nonreciprocal response can also be expected in longitudinally nonuniform structures realized in nonlinear materials,[2] viable alternatives to the Faraday effect can be provided by graded amplifying media[3] or quadratic waveguides rendered asymmetric along the propagation direction. The latter approach, in particular, can take advantage of quadratic cascading in crystals with a substantial parametric response, such as periodically poled lithium niobate.[4] Cascading of quadratic nonlinearities, in fact, has provided novel solutions for all-optical signal switching and processing, including the optical counterparts of electronic components such as transistors and modulators.[5–8]

An all-optical "diode" (AOD) is a spatially nonreciprocal device which allows unidirectional propagation of a signal, acting as an optical isolator at a given wavelength (λ). In the ideal case, its transmission is 100% in the "forward" direction ($T_\lambda^+=1$), while it vanishes for "backward" propagation ($T_\lambda^-=0$), yielding a unitary contrast $C=(T_\lambda^+-T_\lambda^-)/(T_\lambda^++T_\lambda^-)$. The first demonstration of a nonreciprocal device based on cascading reported by Treviño-Palacios, Stegeman, and Baldi utilized a linear asymmetry in the guided-wave vector profile along a liquid niobate (LN) channel for second-harmonic generation (SHG).[4] The weak linear perturbation, introduced by depositing a thin photoresist layer, resulted in a limited contrast.

A high contrast AOD can be obtained by engineering SHG *cascading* effects in forward and backward propagation through proper tailoring of the *nonlinear* response of a channel waveguide. This approach can be effectively exploited by making use of quasiphase matching (QPM) via periodic poling of ferroelectrics such as $LiNbO_3$.[9]

In this letter, we report the demonstration of a truly unidirectional device based on cascaded nonlinearities. Using a suitably designed QPM grating in an annealed proton-exchanged (APE) $LiNbO_3$ waveguide,[10] we have implemented an optical diode exhibiting an isolation figure of merit close to the ideal value of 100% at $\lambda=1.55\,\mu$m.

The QPM profile used for the AOD is sketched in Fig. 1: a uniform QPM grating of overall length L and period Λ_0 is perturbed by a localized "defect," i.e., an isolated domain of extension $\delta L\neq\Lambda_0/2$, inserted at $z=L_1<L/2$. The structure allows cascading of two parametric interactions occurring in the uniform QPM segments L_1 and $L-L_1-\delta L$: standard SHG followed by *seeded* SHG.[11] The latter is controlled by the defect, which locally changes the phase relationship between the fundamental (FF) and second harmonic (SH) waves by the amount $\Delta\varphi=(2\cdot\delta L/\Lambda_0-1)\pi$.

For maximum SHG efficiency, the period Λ_0 equals twice the coherence length of the interaction involving the lowest-order (TM_{00}) guided modes at λ and at $\lambda/2$ in a *z*-cut APE LN channel waveguide. A proper placement (L_1) and length (δL) of the defect can maximize the forward FF transmission by fully restoring the fundamental power at the output via cascaded up-and-down conversions, whereas the device acts as an efficient frequency doubler in the backward direction, yielding negligible FF transmission.

Due to the intrinsic power dependence in seeded SHG, the diode response varies with excitation.[10] Figure 2 is a contour plot of the calculated AOD contrast $(T_\lambda^+-T_\lambda^-)/(T_\lambda^++T_\lambda^-)$ versus the introduced dephasing $\Delta\varphi$ and the excitation $\Gamma^2=\eta_{nor}\cdot P_{IN}\cdot L^2$ in the lossless case for $L_1=0.2\,L$, where η_{nor} is the normalized SHG efficiency and P_{IN} the FF input power. The contours identify contrasts ranging from 20% to 99.9%. It is apparent that values in excess

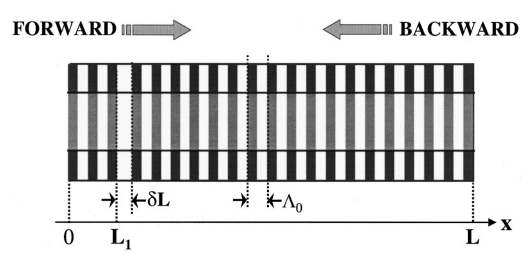

FIG. 1. Sketch of the QPM grating profile used for the all-optical diode (dark and bright sections represent domains with positive and negative nonlinearity): A dephasing domain of length δL is inserted (at $x=L_1$) inside an otherwise perfectly uniform grating of period Λ_0 of overall length L. The arrows indicate nominal forward and backward propagation directions, respectively.

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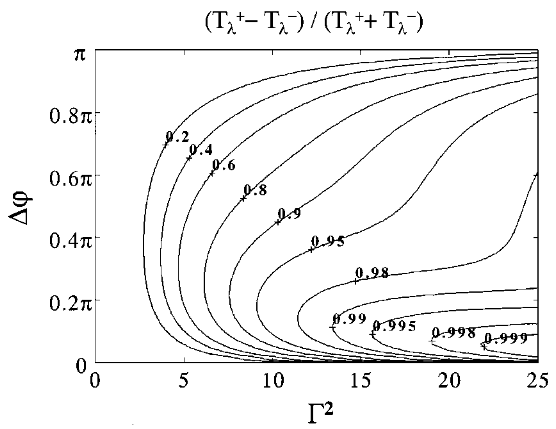

FIG. 2. Contour plot of the AOD figure of merit $(T_\lambda^+ - T_\lambda^-)/(T_\lambda^+ + T_\lambda^-)$ vs $\Gamma^2 = \eta_{\rm nor} \cdot P_{\rm IN} \cdot L^2$ ($\eta_{\rm nor}$ being the normalized SHG efficiency, and $P_{\rm IN}$ the input power) and $\Delta\varphi = (2 \cdot \delta L/\Lambda_0 - 1) \cdot \pi$ for $L_1 = 0.2 \cdot L$, in the lossless case. The labels identify the contrast values on the contours.

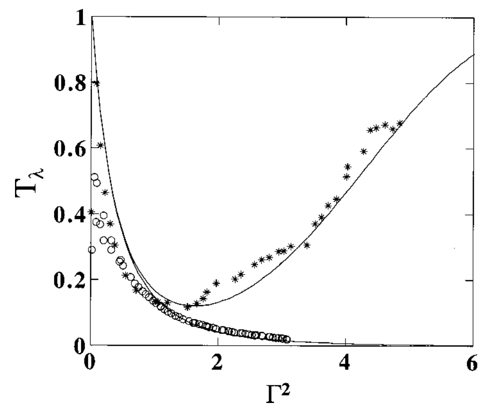

FIG. 4. Measured forward (T_λ^+ :*) and backward (T_λ^- :○) transmissions (normalized to their value for $P_{\rm IN} \to 0$) vs input power $P_{\rm IN}$, along with the theoretical predictions (solid lines) for a waveguide with $\delta L = 8.1\ \mu$m, $L_1 = 8$ mm, $\eta_{\rm nor} = 23.6\%\ {\rm W}^{-1}\,{\rm cm}^{-2}$ and losses of 0.68 and 0.8 dB/cm at 1.55 and 0.775 μm, respectively.

of 95% can be expected in a wide interval of $\Delta\varphi$ for inputs beyond $\Gamma^2 = 10$.

After identifying the most suitable QPM profiles for implementing an AOD, they were realized by electric field poling on 500-μm-thick *z*-cut LN substrates. The QPM gratings had an overall length $L = 4$ cm and a period $\Lambda_0 = 14.7\ \mu$m. Channel waveguides included 1-mm-long mode filters and 1.5-mm-long mode tapers on each end, and were fabricated on the poled substrates by proton exchange in benzoic acid through 12-μm-wide mask openings to a depth of 0.71 μm, followed by annealing at 327.5 °C for 26 h.[12]

First the normalized SHG efficiencies $\eta_{\rm nor}(\%{\rm W}^{-1}\,{\rm cm}^{-2})$ and propagation losses α (dB cm^{-1}) were assessed through a low-power continuous-wave (cw) measurement. The high-power response was then tested with the experimental setup sketched in Fig. 3. The 1.55 μm quasi-cw source consisted of a tunable external cavity diode laser (ECDL), followed by an electro-optic amplitude modulator (EO-AM) and two cascaded erbium doped fiber amplifiers (EDFAs), yielding a train of 20 ns flattop pulses at 1 kHz repetition rate, with peak powers of several Watts. Before being coupled into the $LiNbO_3$ waveguide, the signal passed through a narrow-bandwidth (0.1 nm) fiber Bragg grating (FBG) to filter out all spurious spectral components around 1.55 μm.

For each input peak power $P_{\rm IN}$, we recorded the generated SH and the transmitted FF in forward and (after rotating the sample by 180°) backward propagation. For each input pulse, we extracted the corresponding output peak value, in order to directly compare the experimental results with the calculated stationary response of the device.

Figure 4 shows (symbols) the experimental results for an AOD with a dephasing domain of length $\delta L = 8.1\ \mu$m, placed at $L_1 = 8$ mm in a waveguide with normalized efficiency $\eta_{\rm nor} = 23.6\%\ {\rm W}^{-1}\,{\rm cm}^{-2}$ and losses of 0.68 and 0.8 dB/cm at FF and SH, respectively. The data refer to transmission at 1.55 μm, normalized to the corresponding value for small $P_{\rm IN}$ both in forward (T_λ^+: "*") and backward (T_λ^-: "○") propagation.

The measured AOD response is in good agreement with the numerical predictions (solid lines in Fig. 4). As expected, beyond a threshold input ($P_{\rm IN} \approx 1.6$ W), forward and backward transmissions depart from each other: the defect-induced *seeded* SHG makes the forward transmission increase again, whereas the backward FF decreases monotonically for increasing excitations. For $P_{\rm IN} = 3.1$ W, a record contrast $(T_\lambda^+ - T_\lambda^-)/(T_\lambda^+ + T_\lambda^-) = 90\%$ was obtained.

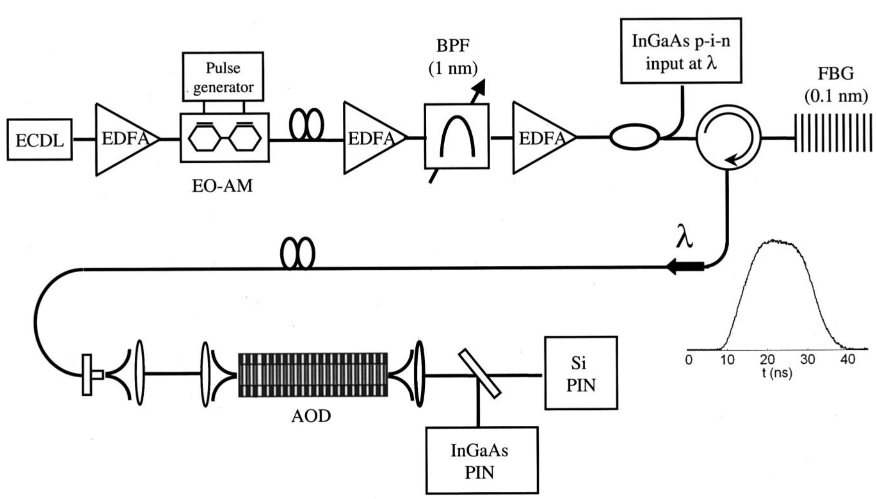

FIG. 3. Setup for the characterization of the AOD response at high powers. The inset shows the actual pulse shape at the input of the device. (ECDL=external cavity diode laser, EDFA=erbium-doped fiber amplifier, EO-AM=electro-optic amplitude modulator, BPF=band pass filter, PIN=p–i–n junction photodiode, FBG=fiber Bragg grating).

Higher values could not be reached due to the onset of parametric oscillations, but will be pursued in samples with a small amount of phase mismatch in order to slightly reduce the parametric gain.

In conclusion, we have reported the demonstration of an integrated power-dependent all-optical diode in a periodically poled LN waveguide, operating with >90% rejection in the third spectral window for fiber communications. This result confirms the potential of QPM engineering in devices based on quadratic cascading for all-optical signal processing.

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